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Evaluation of sulfate attack from CCPS for sustainable construction of a road embankment in Illinois, United States

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ABSTRACT

The readily available supply of coal and its use in coal burning electric generating plants has resulted in production and accumulation of large quantities of Coal Combustion Products (CCPs), primarily fly ash and bottom ash. Fly ash has long been recognized as a construction material used frequently in civil engineering construction, such as conventional concrete, structural fills, embankments, and road bases/subbases. Several projects have successfully been completed within the last two decades where CCPs from burning of Illinois coal have been used as a part of concrete and other value-added products. However, effects of high soluble sulfate content in the CCPs, when used as environment, e.g. embankment, on the strength and durability of conventional concrete structures buried into this material have not received due attention. Consequently, large scale utilization of Class F CCPs is still very limited. Several hundred thousand cubic yards of pond ash from burning of Illinois coal has recently been used for the construction of embankments for a major interchange in Illinois. However, concerns about the high soluble sulfate content in the pond ash and uncertainty about its effects on the buried concrete structures, e.g. light pole and traffic light foundations, concrete pipes, and other similar structures, have limited the possible use of larger quantities of the pond ash. This paper presents the results of a study

focused on quantifying the effects of high soluble sulfate content of pond ash on conventional concrete structures buried into this material. Results presented show that high soluble sulfate content in the pond ash from burning of the Illinois coal is not likely to cause substantial deterioration of concrete elements buried in the embankment made from the pond ash.

Keywords: Coal Combustion products, fly ash, length change, pond ash, sulfate attack

1. INTRODUCTION

The coal and utility industries are among the major sources of mining and industrial wastes. The readily available supply of coal and its use in coal burning electric generating plants has resulted in production and accumulation of large quantities of CCPs. During 2013, about 114.7 tons of CCPs were generated by electric utility companies and about 45% of the total CCPs produced were used in various applications (ACAA, 2015), compared to only 10% used in early 90s (Dube, 1994), approximately 29% in 2000 (Kelly and Kalyoncu, 2002), and approximately 33 percent in 2001 (Kalyoncu, 2003). The remaining products are disposed off in landfills and ash ponds. With the expected growth in power generation, the industry is faced with a lack of available disposal space, disposal and storage costs, and environmental consequences for surrounding communities. Figure 1 shows the production, use, and percentage use of fly ash in the last 10 years.

Within the past 30 years, the concrete industry has given special attention to the safe and economical utilization of these CCPs. Current research on the beneficial use of CCPs has identified several promising uses for these materials. In addition to use in concrete, CCPs have successfully been used in the agricultural industry, blasting grit and roofing material, cement clinker raw feed, flowable fill, grout, mineral filler, mining applications, snow and ice control, wallboard, roller compacted concrete, structural fill, embankments, and soil stabilization (ACAA, 2015). Several case histories of utilization of coal combustion products in construction projects are available in published literature (Golden, 1986; Korcak, 1998; Kumar et al. 1999, 2000, 2001, 2002; Kumar, 2002, 2003, 2004; Kumar and Stewart, 2003a and b; Lovell et al. 1997; Naik et. al., 1997; Schroeder, 1994; Seals et al. 1972; Tikalsky and Carrasquillo, 1989). However, information on any detailed study where CCPs are used as environment instead of products, and the effects of high sulfate content of CCPs on the concrete structures when they are embedded or placed in contact with this ash, is not available in published literature. Therefore, the concerns raised by engineering community regarding the uncertainty about the effects of high sulfate content of CCPs from burning of Illinois coal on the buried concrete structures needs immediate evaluation.

Concrete structures such as foundations of light poles, foundations of traffic signals, concrete pipes, concrete pavements, and other similar structures remain in contact with surrounding soils during their life time. The physical and chemical properties of the surrounding soils are known to have significant effect on the strength, durability, and long-term performance of these concrete structures. Therefore, if these concrete structures need to be embedded or placed in contact with soils or similar materials having chemical composition which can have detrimental effects on the performance of the concrete, a detailed investigation to quantify the effects must be performed before placing the concrete in direct contact with these soils or materials.

According to Mehta (2000) the presence of high concentrations of sulfate in soil or water should not lead anyone to conclude that the concrete deterioration must have been caused by chemical sulfate attack. Published literature indicates that deterioration to concrete in sulfate rich soils could results from a physical attack or chemical attack. The physical attack is caused by pressures resulting from salt crystallization in the pores of concrete which cause cracking, flaking, and spalling in concrete. The chemical attack involves loss of strength and adhesion associated with formation of gypsum and ettringite resulting from decomposition of cement paste by the penetrating sulfate ions.

Mehta (1992) reported that permeability of concrete rather than cement chemistry appears to be the most important factor in sulfate attack. Sulfate attack is seldom found to be the sole phenomenon responsible for the deterioration of concrete structures. Although, formation of ettringite and expansion of concrete due to formation of ettringite is considered as the consequence of chemical sulfate attack, there is no direct correlation between volume of ettringite formed and expansion.

Figure 2 shows a picture of an ash pond of a coal burning power plant in Illinois, USA. Coal combustion products from burning of Illinois coal are known to have high soluble sulfates. Tests on the pond ash shown in Figure 2, conducted by the Department of Transportation show that soluble sulfate content of CCPs from burning of Illinois coal is over 2300 parts per million (ppm). According to some published studies, sulfate contents of this level, if placed in contact with concrete, may affect the strength and durability of the concrete structures.

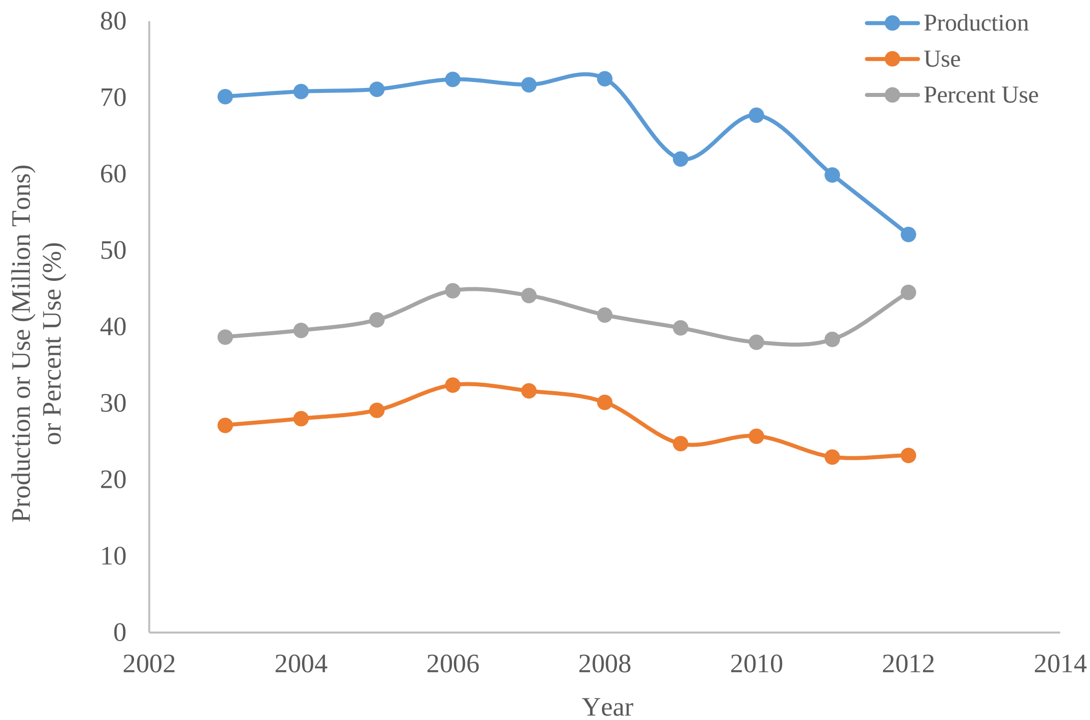

Figure 1 Production, use, and percent use of fly ash (data from ACAA)

Figure 2 Picture of an ash pond of a coal burning power plant in Illinois

Several researchers have conducted studies on the possible effects of sulfates on conventional concrete. Most of these studies used the standard ASTM procedures. Currently, ASTM describes two test methods to evaluate the performance of cements in sulfate rich environments which are ASTM C452 (Standard Test Method for Potential Expansion of Portland-Cement Mortars Exposed to Sulfate) and ASTM C1012/C1012M-13 (Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution). Both of these methods recommend use of length change of mortar specimens after immersing them in the sulfate solution having standard concentration as the measure of sulfate resistance. However, some studies have shown that sulfate attack also causes reduction in strength. Both of the ASTM test methods have been the subject of much criticism. Many researchers, e.g., Brown (1981), Cohen and Mather (1991), Idorn et al. (1992), Mehta (1975 and 1992), Mehta and Gjorv (1974), and Tumidajski and Turc (1995), have expressed concerns that the ASTM procedures do not adequately simulate the field performance.

According to PCA (2015), "sulfate attack and salt crystallization are more severe at locations where the concrete is exposed to wetting and drying cycles, than continuously wet cycles. For the best defense against external sulfate attack, concrete with a low water to cementitious material ratio (w/cm) (less than 0.45 for moderate sulfate environments and less than 0.40 for more severe environments) should be used along with cements or cementitious material combinations specially formulated for sulfate environments." March 2003 issue of Concrete Technology Today published by PCA presents results of a field study where concrete specimens were tested under severe field environmental conditions which included alternate wetting and drying cycles. The study showed that the concrete specimens that were exposed to field environmental conditions of the test suffered significantly more damage than equivalent specimens tested using standard tests. It is important to note that none of the studies completed so far provide results and information which represents the effects of soluble sulfate contents in CCPs on the concrete structures buried into this material. As a part of the overall study, several mortar specimens made with portland cement-sand mortar mixes, portland cement-sand-silica fume (5%) mortar mixes, and plain portland cement concrete mixes were prepared and tested. However, selected results from the study are presented in this paper.

2. EXPERIMENTAL PROGRAM

As pointed out earlier, ASTM suggests two test methods to evaluate the performance of cements in sulfate rich environments. Both of the methods recommend the use of length change of mortar specimens as a measure of the effect of sulfates, after immersing them in sulfate solution having standard concentration. In order to more directly evaluate the effect of sulfate rich CCPs, solution referred to as "fly ash solution" was prepared using pond ash, in addition to the sulfate solution prepared as per the ASTM standard. Moreover, in addition to the length change tests, specimens were tested for weight change, Relative Dynamic Modulus (RDM), and compressive strength.

2.1. Preparation of Solutions

ASTM 1012-04 recommends using 5% sodium sulfate solution to evaluate performance of concrete in sulfate rich environment. Therefore, the sodium sulfate solution was prepared by mixing 50 grams of sodium sulfate with 1000 ml of water. Preparation of "fly ash solution" was challenging since there is no standard procedure available. In order to prepare the fly ash solution, procedure similar to the one used to determine water soluble sulfate content in soil as per AASHTO T290 (AASHTO 2007) was used. To prepare the solution, pond ash and tap water were mixed in the ratio of 100 g of pond ash and 300 ml of tap water. This ratio of pond ash to water is the same ratio used in AASHTO T290 test procedure. Initially, the solution was mixed for different time intervals, varying from 1 hour to 10 hours, and the amount of soluble sulfates was measured after each time period. From this preliminary study, it was determined that the solution needs to be mixed for 10 hours to get the same amount of water soluble sulfates as obtained from AASHTO T290. Large quantities of solutions were then prepared in 5 gallon drums by shaking (tumbling) them in a special machine for 10 hours. After shaking was complete, the solution was filtered through a filter paper to remove solid fly ash particles and stored in air-tight drums for further study.

2.2. Specimen Preparation

Cement mortar specimens were prepared in general accordance with ASTM C305 "Standard Method of Mixing of Hydraulic Cement pastes and Mortars of Plastic Consistency". The raw materials used consisted of ASTM Type I portland cement as a binder, natural sand as fine aggregates, tap water, and micro-air as air-entraining admixture. The following three types of specimens were prepared using the mortar mixes.

1.Prisms of size 1 x 1x 11¼ inches having gage length of 10-inches to perform length change, weight change, and RDM tests.

2.Cubes of size 2-inch to perform compressive strength tests.

Specimens were allowed to cure in the molds for 24 hours and then in water for either 7 or 28 days. After the initial curing period, specimens were placed in sulfate solution, or fly ash solution, or left in water. Specimens left in water were used as control specimens to measure the relative effect.

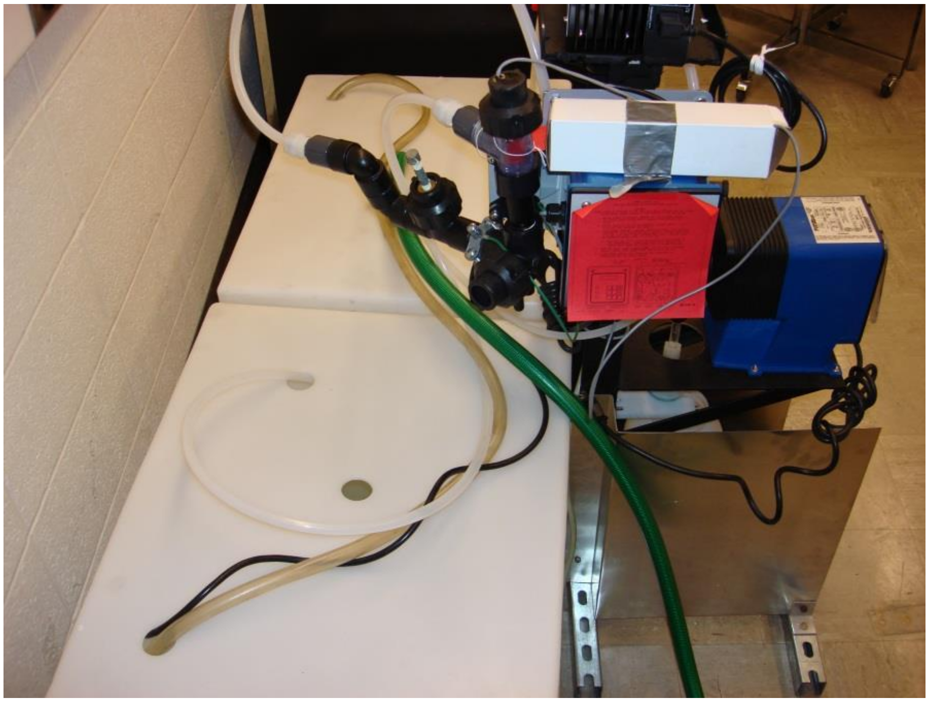

Figure 3 Testing of mortar specimens placed in sulfate solution maintained at pH between 7 and 7.2 is in progress

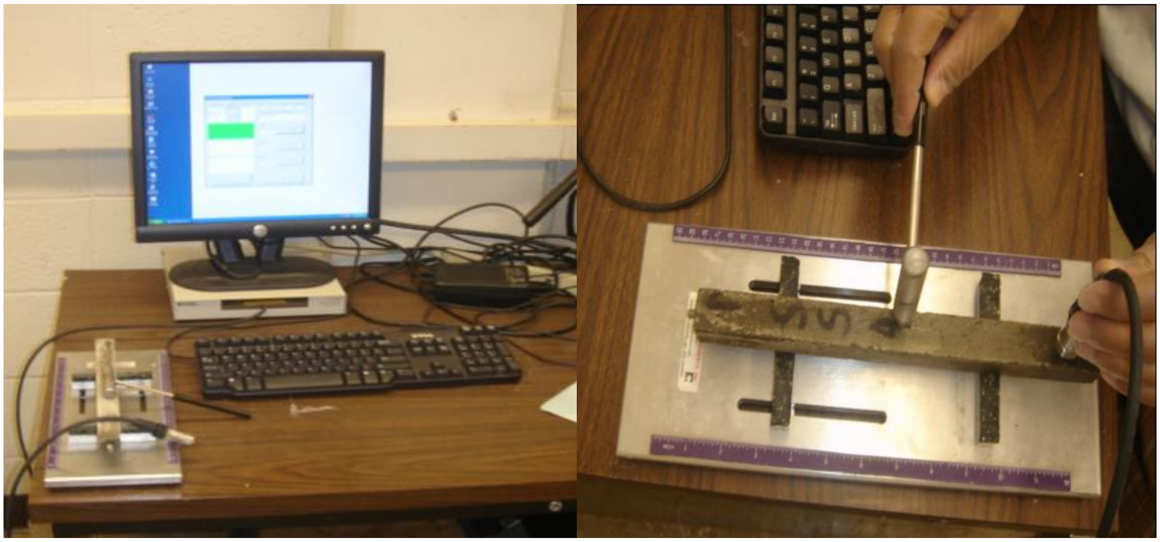

Figure 4 RDM test on a prism specimen in progress

2.3. Testing Procedures

Although ASTM procedures use the length change as the measure of impact of sulfate on concrete mortars, in this study several other parameters were measured. When cement mortar or concrete specimens are placed in water or solutions, the pH of the water or solution increases. Some studies (e.g., Mehta and Gjorv, 1974) suggest that during the sulfate testing, the pH of the solution should be maintained close to 7. Therefore, a test setup similar to the one used by Mehta and Gjorv (1974), and shown in Figure 3, was manufactured to automatically control the pH of the sulfate and fly ash solutions to a value between 7 and 7.2. However, specimens placed in the sulfate and fly ash solutions, without any pH control were also tested. Specimens placed in the sulfate solution, fly ash solution, and water were removed at regular intervals to test for compressive strength, length change, weight change, and RDM. Figure 4 shows a picture of the RDM test in progress.

3. RESULTS AND DISCUSSION

For this investigation, three types of solutions (sulfate solution prepared as per ASTM standard, fly ash solution, and water) and two types of pH control (automatic pH control and no pH control) were used. In addition, tests were performed on two sets of specimens, i.e., placing in sulfate and fly ash solutions after 7 days of curing in water and placing in sulfate and fly ash solutions after 28 days of curing in water. At least three specimens were tested for each data point.

3.1. Length Change

The change in length of the specimens was measured every week until the change in length became negligible. Figure 5 shows the length change of the prisms made from cement-sand mixtures and kept in the sulfate solution and fly ash solution compared to those kept in water. The specimens were placed in sulfate and fly ash solutions after 7 days of curing. The pH of the solution was not controlled. Results presented in Figure 5 show that the length of the specimens increased with the increase in the age of exposure to the solutions, irrespective of the type of the solution. After 30 weeks of submergence, the strain of specimens placed in water was 110 x 10^{-5}, specimens placed in fly ash was 370 x 10^{-6}, and specimens placed in sulfate solution was 650 x 10^{-6}. It is important to note that the length change of the specimens in the fly ash solution was greater than that for the specimens in water but is less than the change for the sulfate solution prepared as per ASTM standards.

Figure 6 shows the length change for cement mortar prisms submerged in sulfate solution, fly ash solution, and water after 28-days of initial curing in water and no pH control. It is interesting to note that the length change of specimens kept in water and fly ash solution is of the similar order, irrespective of whether they were cured for 7 days or 28 days. However, specimens placed in sulfate solution shown substantial reduction in the length change.

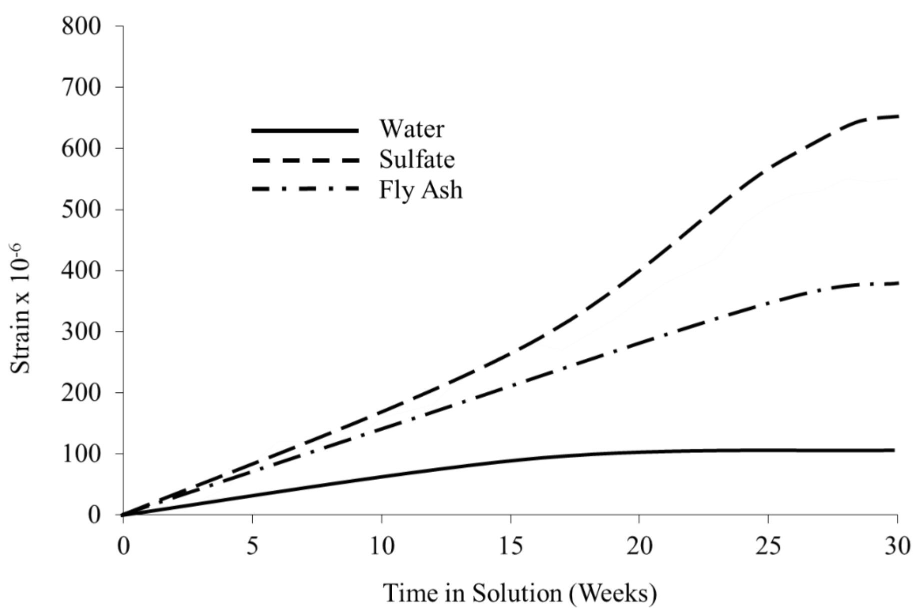

Figure 5 Length change of cement mortar prisms submerged in sulfate solution, fly ash solution, and water (7-days curing in water and no pH control)

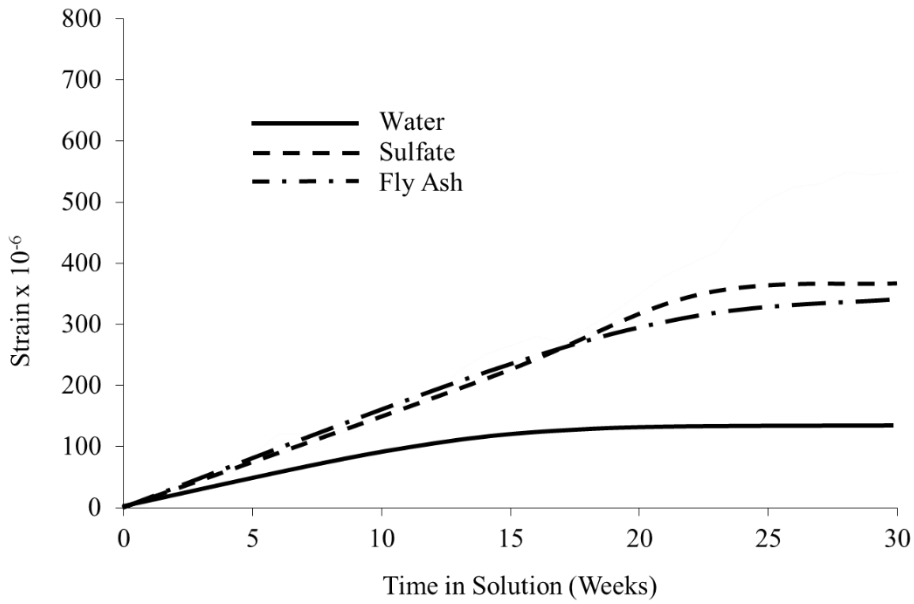

Figure 6 Length change of cement mortar prisms submerged in sulfate solution, fly ash solution, and water (28-days curing in water and no pH control)

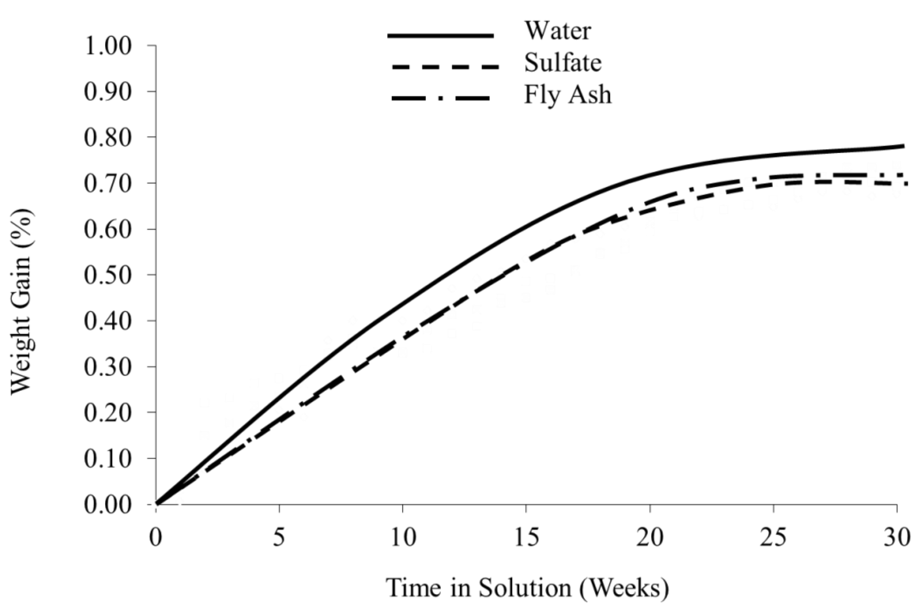

Figure 7 Weight change of cement mortar prisms submerged in sulfate solution, fly ash solution, and water (28-days curing in water and no pH control)

3.2. Weight Change

Figure 7 shows the weight gain of the prisms made from cement-sand mixtures and kept in sulfate solution and fly ash solution as compared to those kept in water. The specimens were placed in sulfate and fly ash solutions after 28 days of curing. The pH of the solution was not controlled. Results presented in Figure 7 show that the weight gain in the specimens placed in sulfate and fly ash solutions was almost the same as that observed in specimens placed in water. The specimens placed in water gained slightly weight more than the specimens placed in sulfate and fly ash solutions.

3.3. Relative Dynamic Modulus (RDM)

The RDM test is also known as a frequency test. The test was performed on prisim specimens of size 1 x 1 x 11.25 inches. The change in frequency of the specimens was measured every week until the change in frequency became negligible. Figure 8 shows the RDM of prisms made from cement-sand mixtures and kept in sulfate solution and fly ash solution compared to those kept in water. The specimens were placed in sulfate and fly ash solutions after 7 days of water curing. The pH of the solution was not controlled. Results presented in Figure 8 show that the RDM for the specimens placed in fly ash solution was almost the same as that was observed for specimens placed in water. However, the RDM of specimens placed in sulfate solution was lower than that specimens placed in water and in fly ash solution indicating lower performance.

Figure 9 shows the pictures of the prism specimens after 50 weeks in fly ash solution, sulfate solution and water. These specimens were used to measure the length change, weight change and relative dynamic modulus. The pictures of the specimens do not show visible signs of any distress, cracking, spalling even after 50 weeks in sulfate of fly ash solution. Therefore, it is the authors' opinion that the level of soluble sulfate observed in the pond ash from burning on Illinois coal may cause slight reduction in durability but are not likely to result in significant deterioration or failure in concrete.

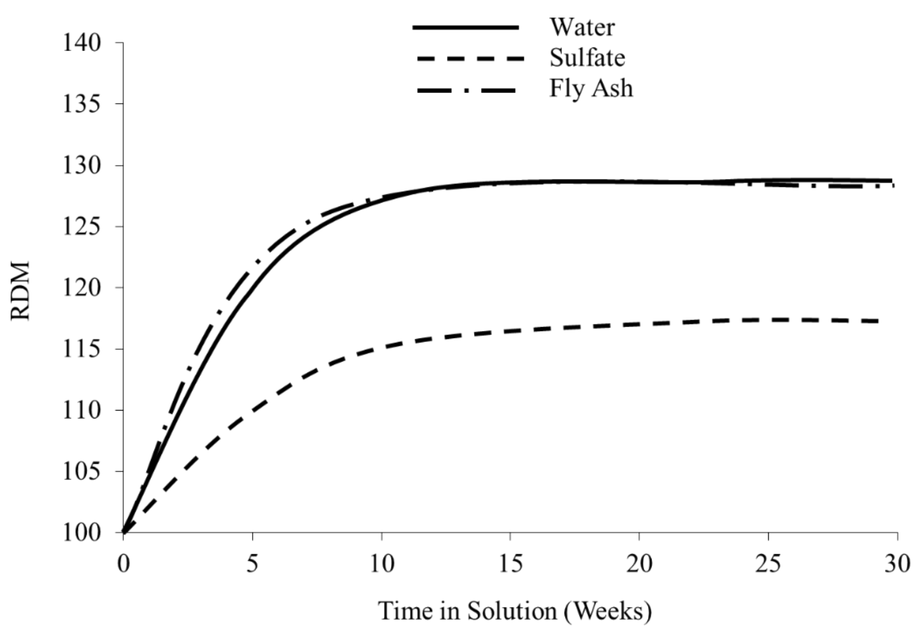

Figure 8 Relative Dynamic Modulus (RDM) of cement mortar prisms submerged in sulfate solution, fly ash solution, and water (7-days curing in water and no pH control)

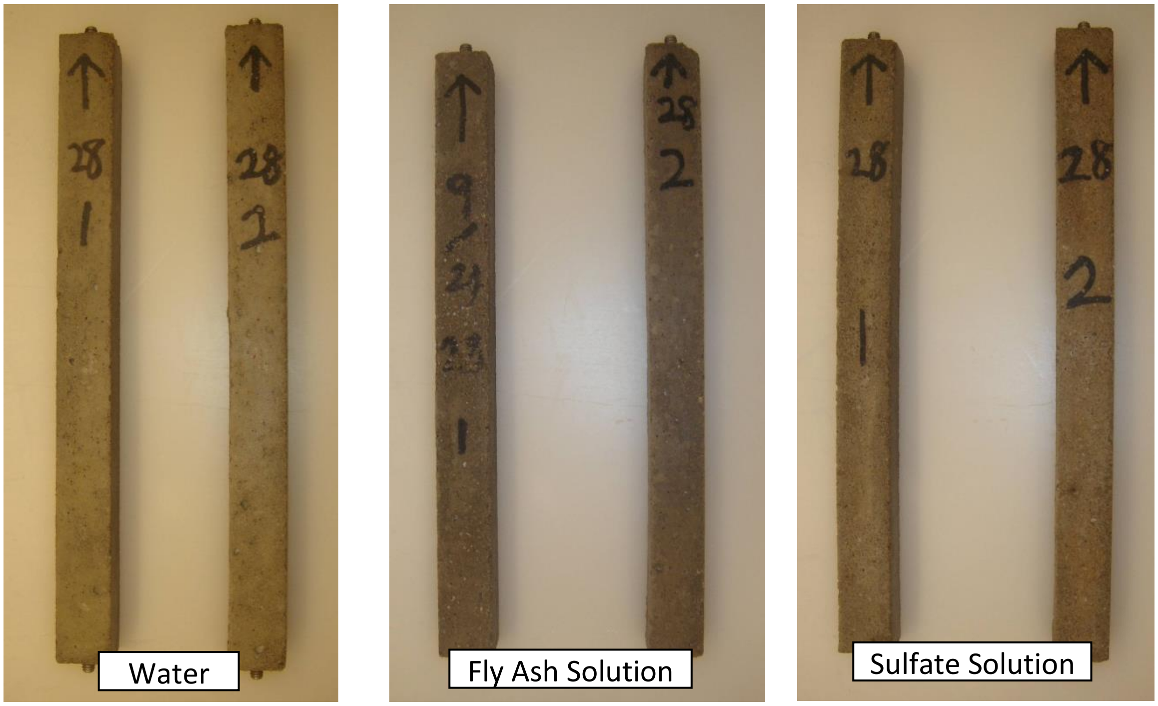

Figure 9 Pictures of specimens after 50 weeks in water, fly ash solution and sulfate solution

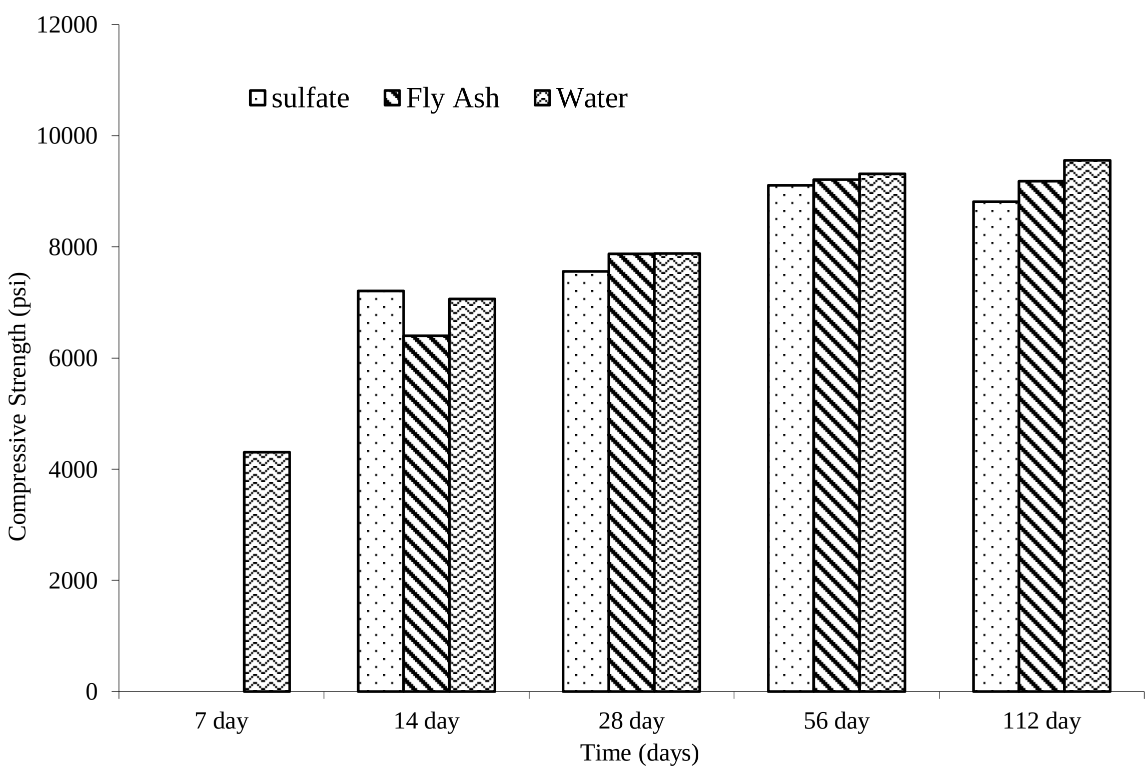

Figure 10 Compressive Strength of specimens placed in sulfate solution, fly ash solution, and water

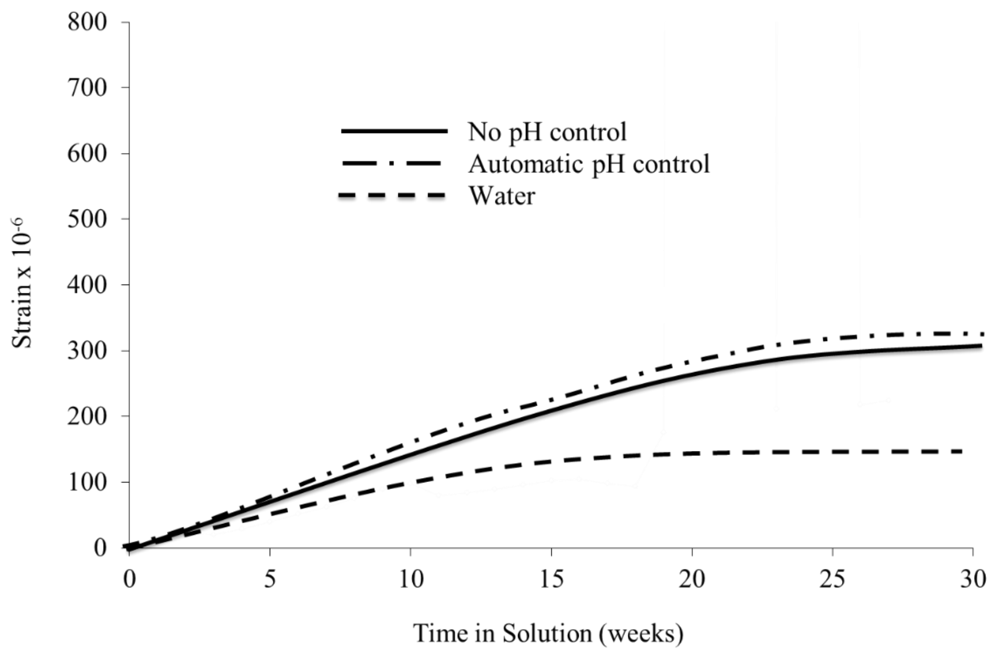

Figure 11 Length change of mortar submerged in fly ash solution (28-days curing in water and no pH control, automatic pH control, and water)

Figure 12 Picture of an embankment construction using CCPs from Illinois coal in progress

3.4. Compression Strength

Figure 10 shows the compressive strength of cement-sand mortar specimens submerged in the sulfate solution and fly ash solution compared to those kept in water. The pH of the solution was not controlled. The specimens were placed in sulfate and fly ash solutions after 7 of curing. Tests were performed at various curing ages. Results presented in Figure 10 show that the compressive strength of specimens placed in sulfate solution and fly ash solution is almost the same as that of specimens placed in water. After 112 days of submergence in the sulfate and fly ash solutions, compressive strength of specimens placed in fly ash solution was approximately 4% lower than that of the specimens submerged in water (control specimens) whereas the compressive strength of the specimens placed in the sulfate solution was approximately 8% lower than that of the specimens placed in water.

3.5. Effect of Solution pH

Figure 11 shows the strain curves for mortar specimens placed in fly ash solution without pH control and with automatic pH control. Specimens were placed in the solution after 28 days of curing in water. As evident from this figure, controlling pH did cause a slightly higher volume change in these specimens. However, the difference in the volume change between no pH control and automatic control was insignificant for these specimens for all practical purposes.

4. CONCLUSIONS

The paper presents results of a study conducted to evaluate the effects of high soluble sulfate content in the CCPs from buring of Illinois coal on the concrete elements buried into these CCPs for its potential use to build an embankment for a major highway in Illinois, USA. The results presented show that (1) the volume change of specimens, in terms of length change, placed in sulfate solution and fly ash solution was slightly greater than that of the specimens placed in water, (2) the weight gain in specimens placed in sulfate solution and fly ash solution was slightly lower than that from the specimens placed in water, and (3) the relative dynamic modulus of specimens placed in the fly ash solution was almost the same as that for specimens placed in water. In addition, the compressive strength from specimens placed in sulfate and fly ash solutions was almost the same as that from the specimens placed in water until about 60 days. However, after about 60 days in sulfate solution or fly ash solution, the compressive strength was observed to be slightly less than those from specimens placed in water.

Although, the sulfate solution and Illinois fly ash solution caused slightly higher length change, slightly lower weight gain, slightly lower RDM, and slightly lower long-term strength, no visible signs of any distress, cracking, spalling were observed on any specimen completely submerged in these solutions Therefore, it was concluded that the level of soluble sulfate observed in the CCPs from burining of Illinois coal may cause slight reduction strength and durability but are not likely to result in significant deterioration or failure of concrete. Figure 12 shows a picture of the construction of an embankment in progress using the CCPs from a coal burning power plant in Illinois. As reported in published literature, sulfate attack is seldom found to be the sole phenomenon responsible for the deterioration of concrete structures.

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